The APS Council has endorsed the establishment, contingent on funding, of the

Herman Feshbach Prize in Nuclear Physics

To recognize and encourage outstanding research in theoretical nuclear physics. The prize will consist of $10,000 and a certificate citing the contributions made by the recipient. The prize will be presented biannually or annually-depends on your contributions.

Herman Feshbach was a dominant force in Nuclear Physics for many years. He co-authored two seminal textbooks, provided the theoretical basis for nuclear reaction theory, and originated the ``Feshbach resonance" used to control the interactions between atoms in ultracold gases. He also made many administrative contributions.

The establishment of this prize depends entirely on the contributions of institutions, corporations and individuals associated with Nuclear Physics. So far, significant pledges have been made by MIT, the DNP, Elsevier, ORNL/U.Tenn, JSA/SURA, LANL, TUNL, and many individuals. But the collection of contributions has begun. Please make a contribution by going online at http://www.aps.org/ Look for the support banner and click APS member or non-member. Another way is to send a check, made out to "The American Physical Society", with a notation indicating the purpose is the Feshbach Prize Fund, to

Darlene Logan
Director of Development
American Physical Society
One Physics Ellipse
College Park, MD 20740-3844

If annual- number of experimentalists winning Bonner prize goes up by >50%

If you have any questions please contact G. A. (Jerry) Miller UW, miller@uw.edu.

Nucleon Electromagnetic Form Factors and Spin: is proton made of 3 quarks?

Gerald A. Miller, UW

Connection between elastic form factors and OAM through models

Model wave functions, compute form factors

OAM content of Models: elastic form factors imply that quark, pion OAM is large

What is not in the talk

- Proton radius - new work
- Transverse densities - slope of G_E is not the real radius
- Transverse densities from dispersion relations:

PHYSICAL REVIEW D **83,** 013006 (2011)

Pion transverse charge density from timelike form factor data

G. A. Miller,[1] M. Strikman,[2] and C. Weiss[3]

PHYSICAL REVIEW C **84**, 045205 (2011)

Realizing vector meson dominance with transverse charge densities

G. A. Miller,[1] M. Strikman,[2] and C. Weiss[3]

A lot of other stuff

Review of all models is absent

History -Definitions

$$\overline{u}(p',\lambda')\Gamma^\mu u(p,\lambda) = \overline{u}(p',\lambda')[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}(p'-p)_\nu}{2M}F_2(Q^2)]u(p,\lambda)$$

$$G_E \equiv F_1 - \frac{Q^2}{4M}F_2,\ G_M = F_1 + F_2$$

F_1 is light-front helicity non-flip, F_2 is light-front helicity flip

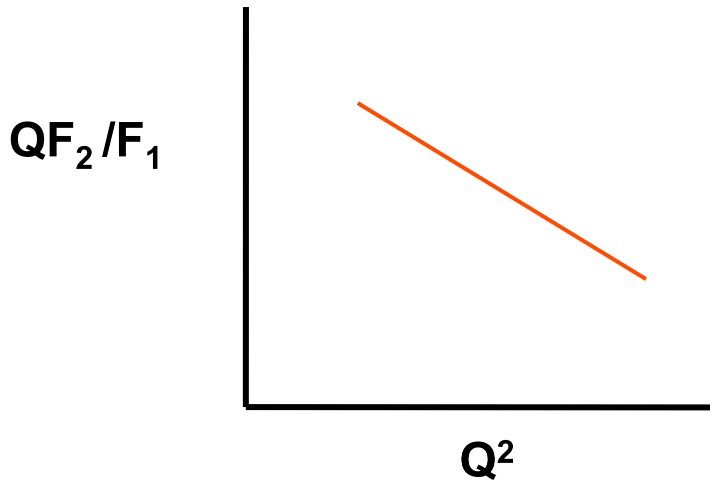
old pQCD:

$$\frac{QF_2(Q^2)}{2M_N F_1} \sim \frac{m_{\text{quark}}}{Q} \rightarrow \frac{G_E}{G_M} = \text{const}$$

Same as non-relativistic

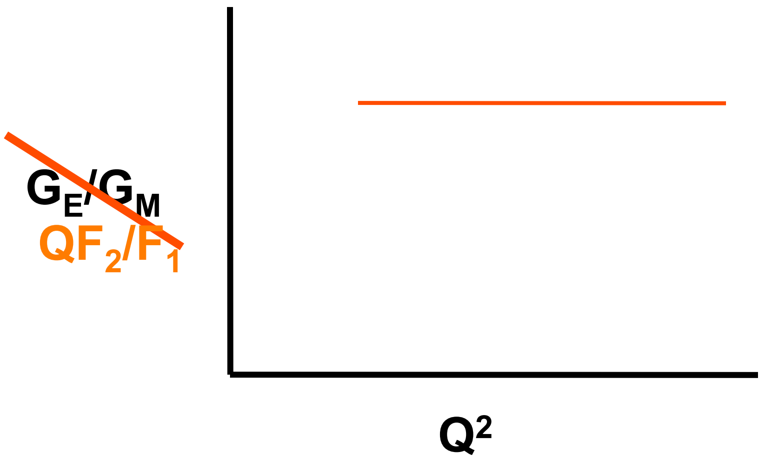
JLab 2000,2002

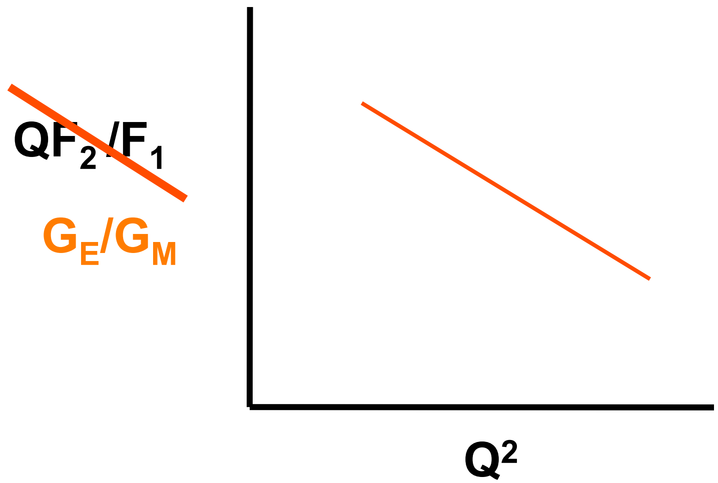
Expectations- Pre Jlab



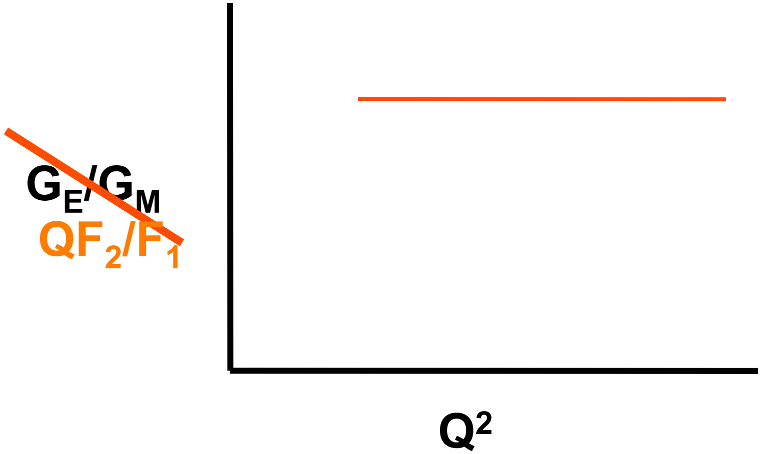
JLab 2000,2002

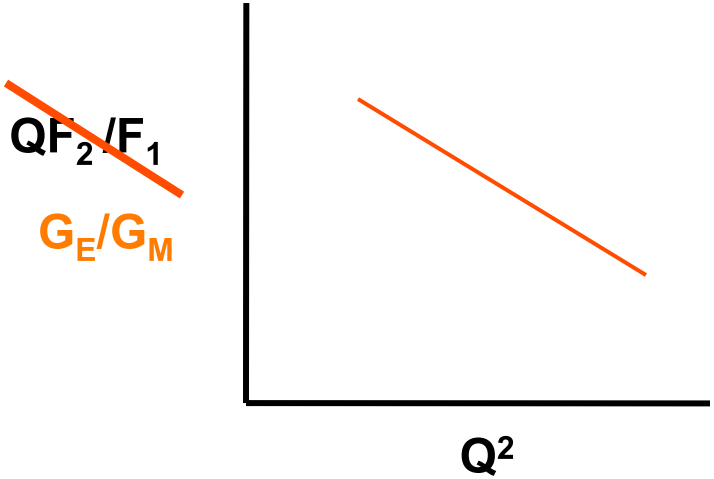
Expectations- Pre Jlab





JLab 2000,2002





Relativistic Wave function

Frank, Jennings, Miller PR C54, 920 (1996)
Relativistic model for color transparency

- 3 quark anti-symmetric
- relative variables, frame independent **Light front variables**
- eigenstate of spin operator- rotational invariant
- reduces to non-relativistic if $m \to \infty$

$\Psi = \Phi(M_0^2) u(p_1) u(p_2) u(p_3 = K) \psi(s_i, t_i)$ Terentev, Coester

spatial dist DIRAC SPINORS spin-ispin color amp

Schlumpf Mom space wf $\Phi(M_0) = N/(M_0^2 + \beta^2)^\gamma$

$\beta = 0.607$GeV $\gamma = 3.5$ $m = 0.267$ GeV

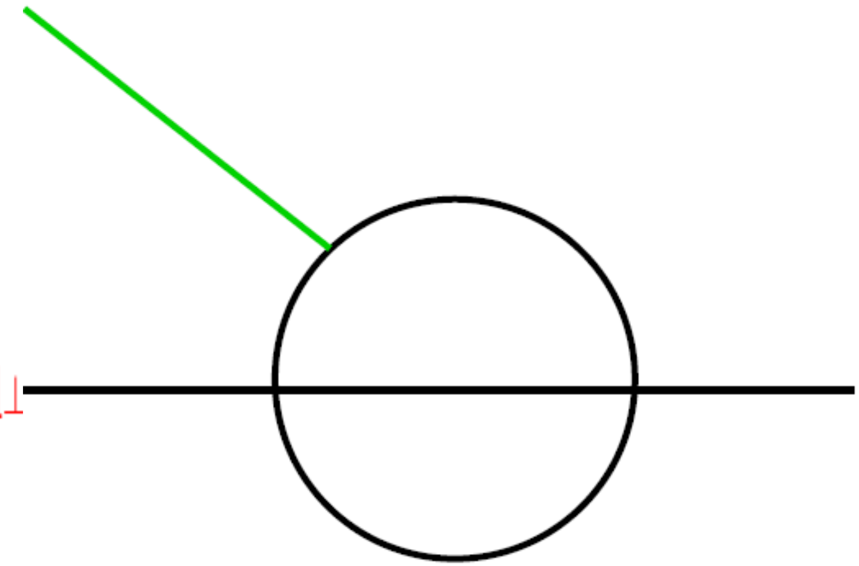
Impulse Approximation

Model proton wave function $\Psi(\mathbf{k}_\perp, \mathbf{K}_\perp, \xi, \eta)$

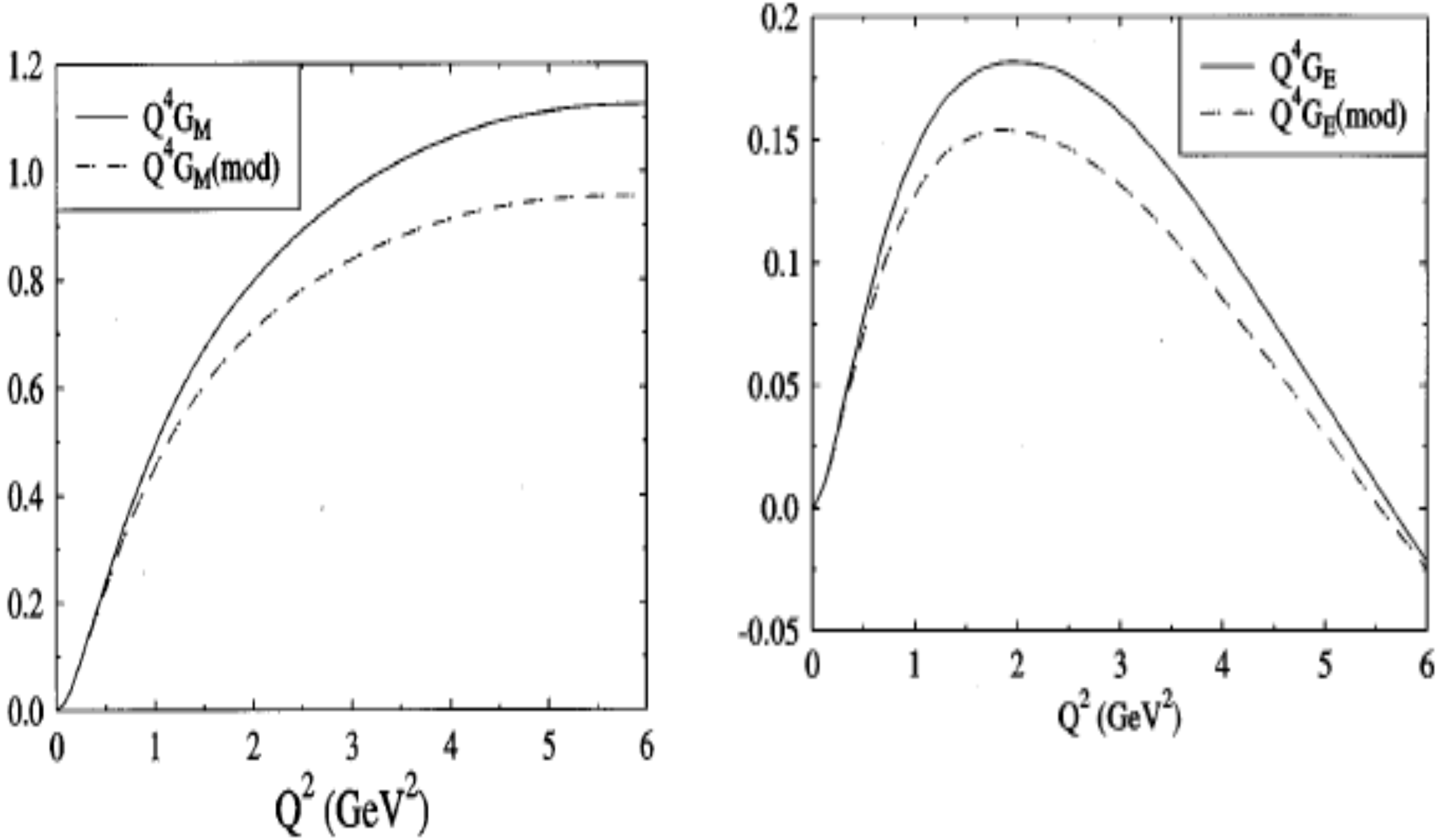
Poincare invariant

Light front variables for boost: $\mathbf{K} \to \mathbf{K} + \eta \mathbf{q}_\perp$

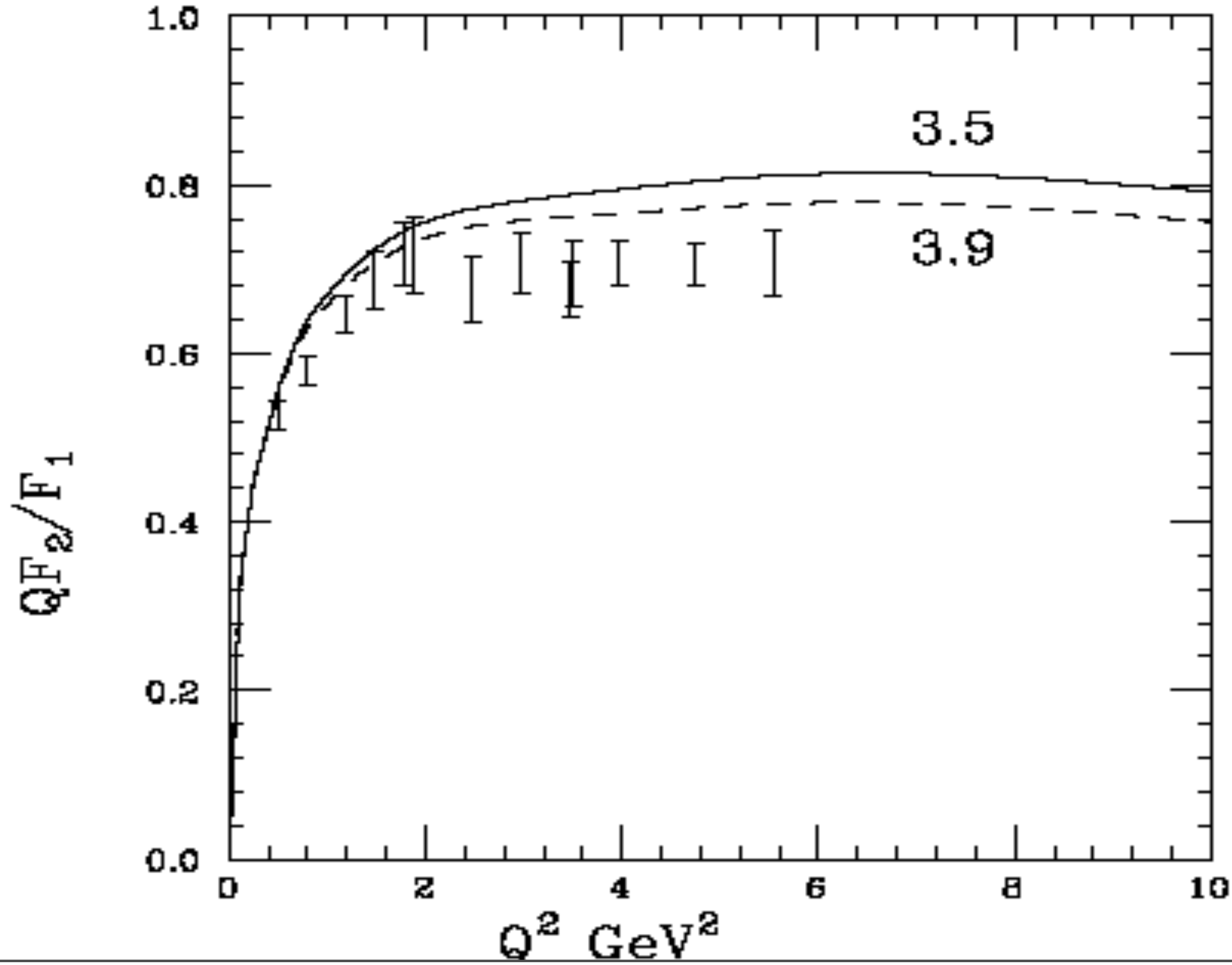
Dirac spinors



1995 Frank, Jennings, Miller



Ratio of Pauli to Dirac Form Factors 1995



Relativistic Explanation

J^+ acts on third quark, other two have 0 spin

$$u(K,s) = \begin{pmatrix} (E(K)+m)|s\rangle \\ \boldsymbol{\sigma}\cdot\mathbf{K}|s\rangle \end{pmatrix}$$

$\boldsymbol{\sigma}_y|s\rangle$: quark spin $\neq$ proton ang mom

lower components $\equiv L_z \neq 0$

$\bar{u}(K',s')\gamma^+ u(K,s) \sim \langle s'|K^+ + i\sigma_y Q|s\rangle$ Large Q

spin non-flip $F_1(Q^2) = \int \cdots Q\Phi\Phi$, flip $QF_2 = \int \cdots Q\Phi\Phi$

$\frac{QF_2}{F_1} \sim Constant$

Miller, Frank **Phys.Rev. C65 (2002) 065205**

Relativistic Explanation

J^+ acts on third quark, other two have 0 spin

$$u(K,s) = \begin{pmatrix} (E(K)+m)|s\rangle \\ \boldsymbol{\sigma}\cdot\mathbf{K}|s\rangle \end{pmatrix}$$

Large OAM associated with relativistic effects

$\boldsymbol{\sigma}_y|s\rangle$: quark spin $\neq$ proton ang mom

lower components $\equiv L_z \neq 0$

$\bar{u}(K',s')\gamma^+ u(K,s) \sim \langle s'|K^+ + i\sigma_y Q|s\rangle$ Large Q

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$\frac{QF_2}{F_1} \sim Constant$

Miller, Frank **Phys.Rev. C65 (2002) 065205**

Spin content - OAM

$$s_\mu \Delta q = \langle N, s|\bar{q}\gamma_\mu\gamma_5 q|N, s\rangle$$

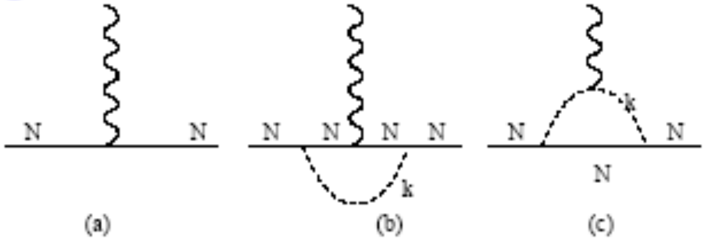
$$\Sigma = \Delta u + \Delta d + \Delta s$$

75 % of proton angular momentum carried by quark spin

Textbook relativistic effect that reduces calculated axial vector coupling constant below NRQM value 5/3

Neutron: Need π cloud effect at low Q^2

Cloudy Bag Model 1980



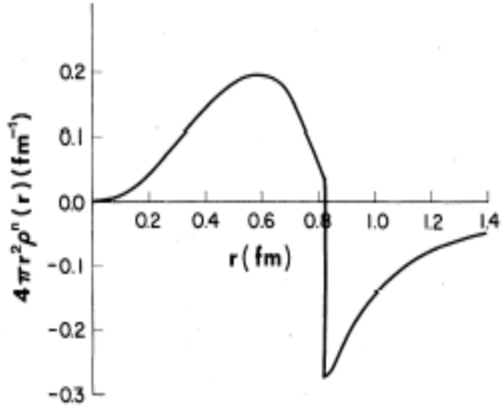


FIG. 11. Neutron charge density.

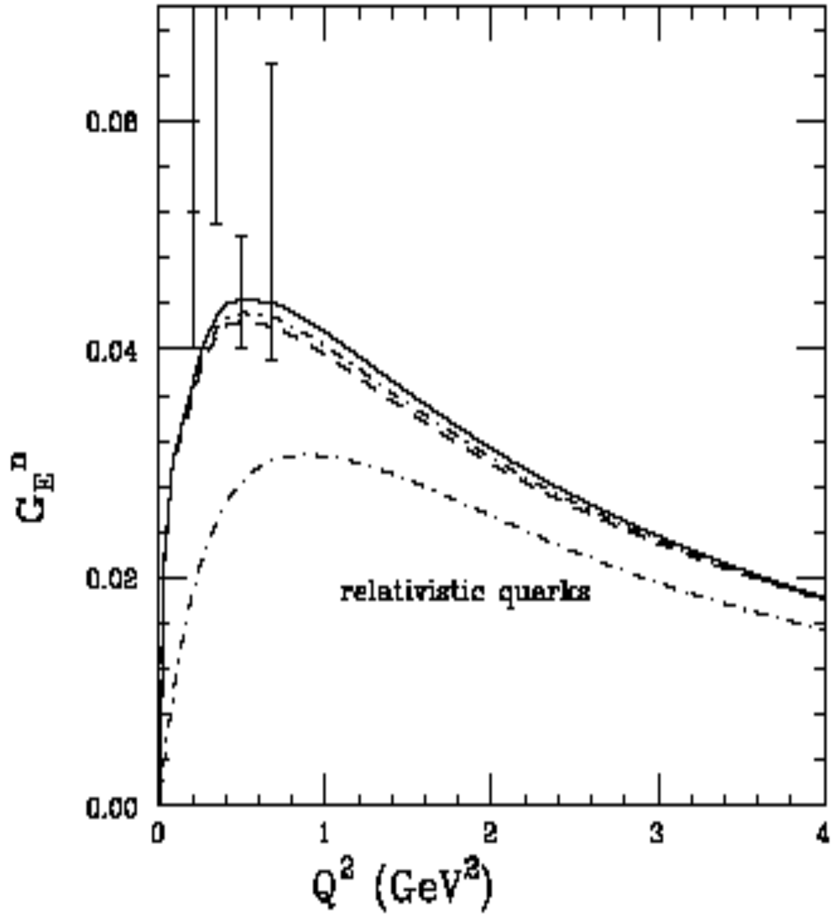
Relativistic treatment needed Feynman graphs, $\int dk^-$

Light front cloudy bag model LFCBM 2002

Miller Phys.Rev. C66 (2002) 032201

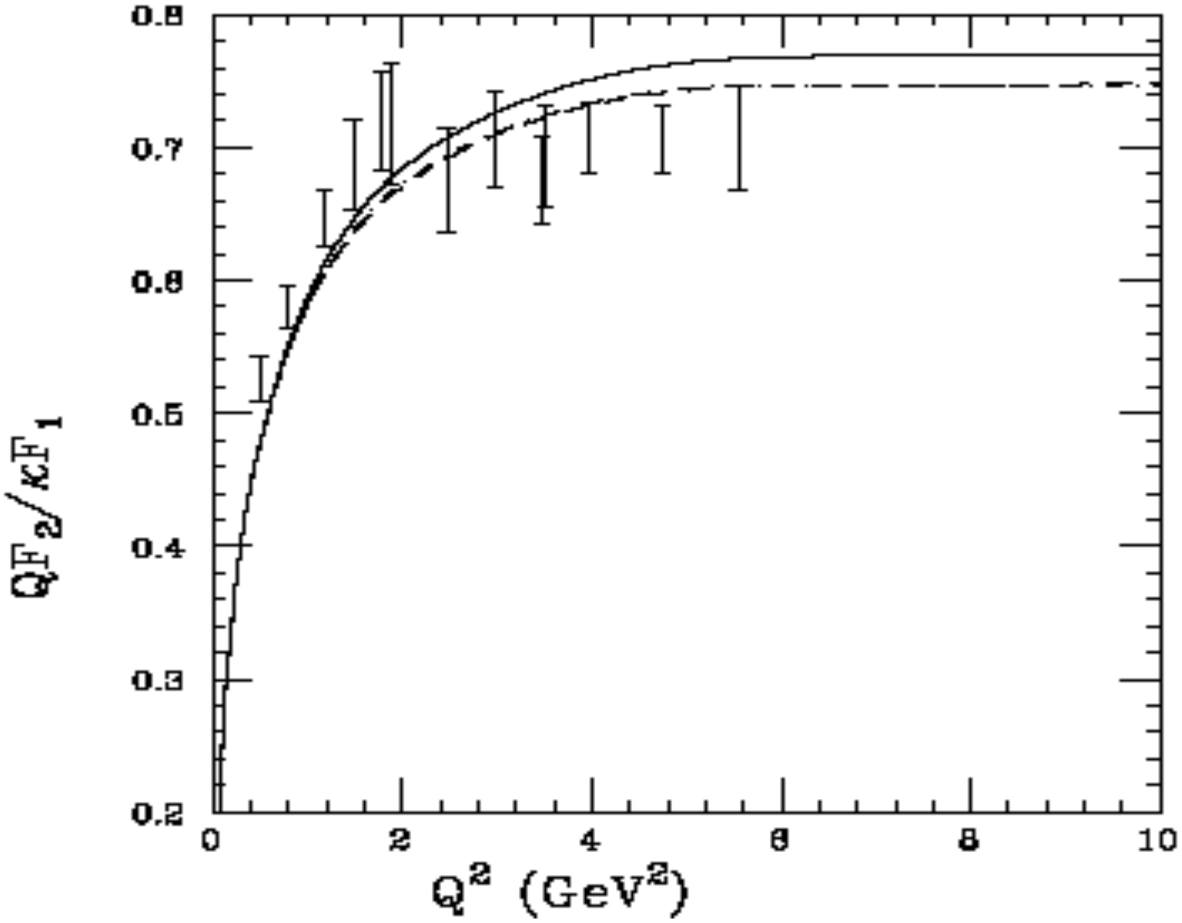
- γN form factors from model (our model)
- rel. πN form factor $\Lambda_{\pi N}$
- Model parameters: $m, \beta, \gamma, \Lambda_{\pi N}$

Neutron Electric Form Factor

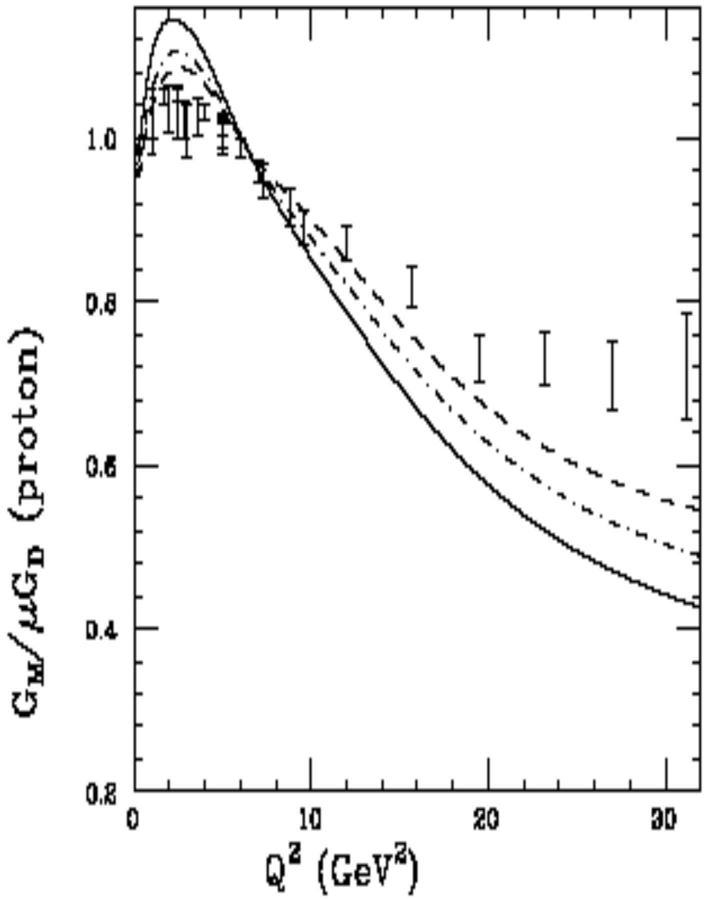


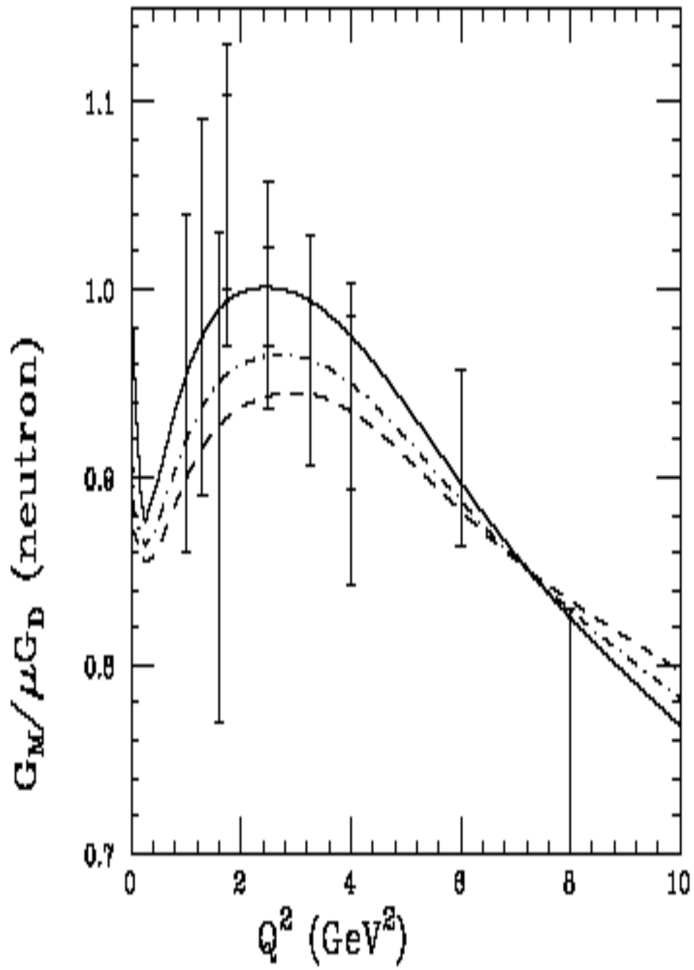
LFCBM 2002- much better data now

Ratio of Pauli to Dirac Form



Two More Form Factors Needed





OAM content of light front cloudy bag model

$$\Sigma \to (Z - \frac{1}{3}P_{N\pi} + \frac{5}{3}P_{\Delta\pi})\Sigma$$

$$\text{Schreiber, Thomas PLB215, 141(88)}$$

$$LFCBM:\ P_{N\pi} \approx .25,\ P_{\Delta\pi} = 0$$

$$\Sigma \to \frac{2}{3}\Sigma \sim \frac{2}{3}\frac{3}{4} = \frac{1}{2}$$

Can now include Δ Alberg, Miller PRL **108 (2012) 172001**

2011 Update model

- In LFCBM G_E/G_M falls too fast with Q^2
- New data -slower fall, flavor decomposition not good Cates et al **Phys.Rev.Lett. 106 (2011) 252003**
- get smaller quark spin?
- Many invariant forms of nucleon wave function
- Cloet & Miller **arXiv:1204.4422** quark di-quark model:
- uses other invariant wave functions

(Brodsky, Hiller, Karmanov, Hwang PRD 2001)

Cloet Miller 2011-12

Scalar diquark

$$\Phi^{\lambda_N}_{\lambda_q\,\lambda_D}(k,p) = \bar{u}(k,\lambda_q)\left[\varphi_1^s + \frac{M}{p^+}\gamma^+\varphi_2^s\right]u_N(p,\lambda_N)$$

$$+\bar{u}(k,\lambda_q)\,\varepsilon^*_\nu(q,\lambda_D)\gamma^\nu\gamma_5\left[\varphi_1^a + \frac{M}{p^+}\gamma^+\varphi_2^a\right]u_N(p,\lambda_N)$$

Axial vector diquark

$$|p\rangle = \frac{1}{\sqrt{2}}|u\,S_0\rangle + \frac{1}{\sqrt{6}}|u\,T_0\rangle - \frac{1}{\sqrt{3}}|d\,T_1\rangle,$$

$$\varphi_1 = \frac{1}{(M_0^2+\beta^2)^\gamma}, \qquad \varphi_2 = c\,\frac{(M_0 - M)}{2\,M}\varphi_1.$$

Plus pion cloud- 9 parameters

χ^2	m	M_s	M_a	c_s	β_s	γ_s	c_a	β_a	γ_a	Λ	$\mu_p\ (\mu_N)$	$\mu_n\ (\mu_N)$
0.078516	0.191	0.414	0.167	1.509	1.226	5.719	0.008	1.104	8.586	1.035	2.794	-1.849

Cloet Miller 2011-12

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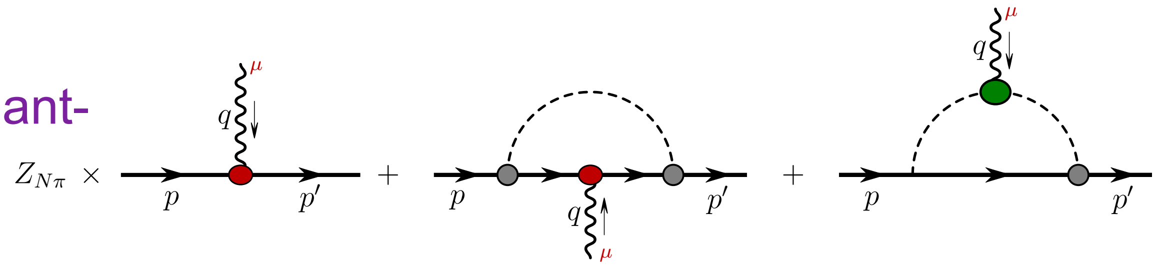
Cloet &Miller '11-'12

Model proton wave function: quark-diquark

Lorentz and rotationally invariant- different forms!

Light front variables

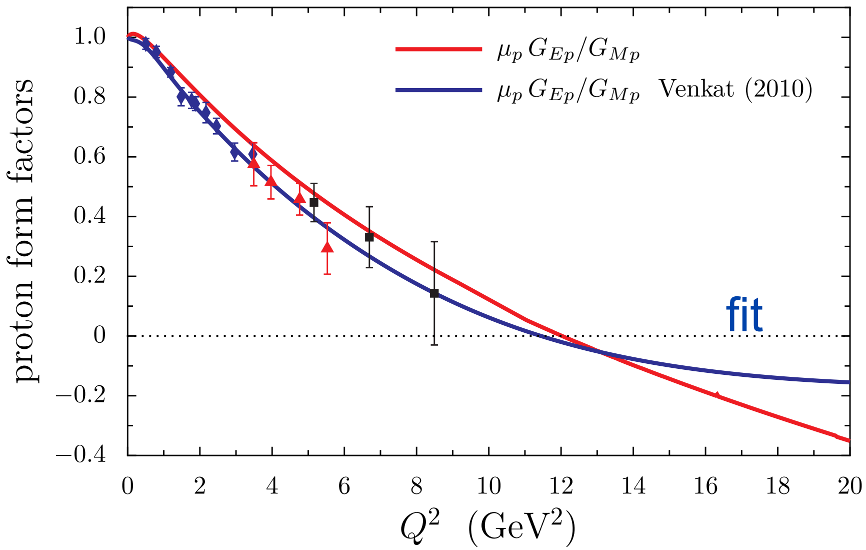
Dirac spinors-orbital angular momentum

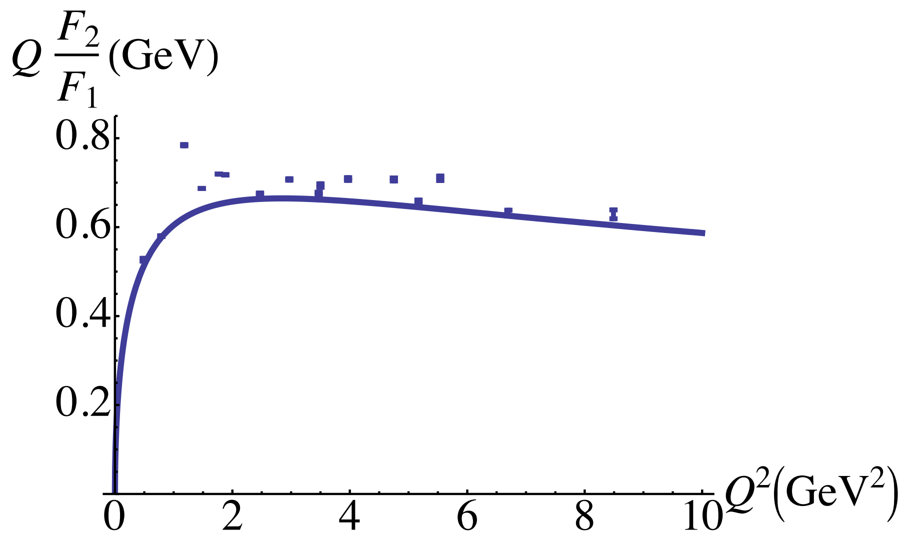


Pion cloud of Light Front Cloudy Bag Model -GAM PRC **66 (2002) 032201**

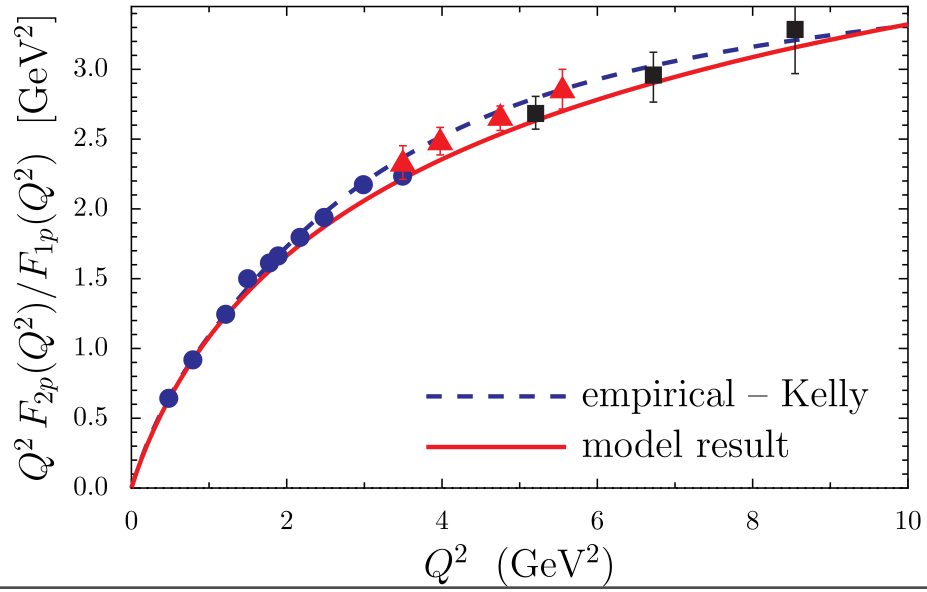
Could be improved according to Alberg Miller **Phys.Rev.Lett. 108 (2012) 172001**

Cloet &Miller '11-'12-proton results

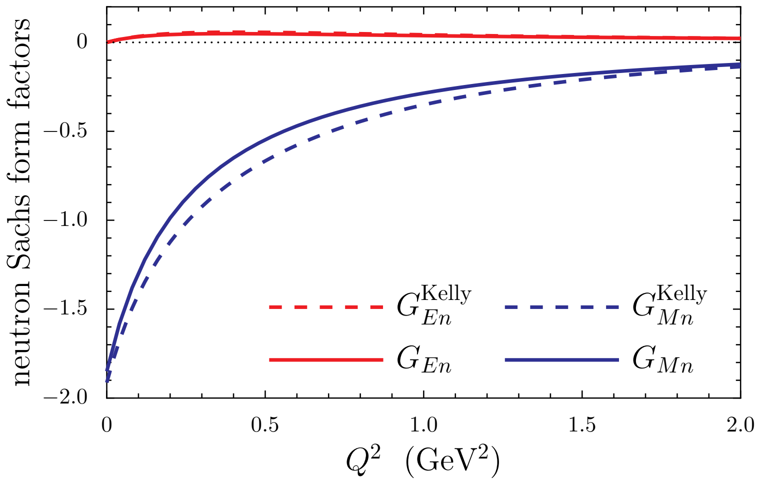


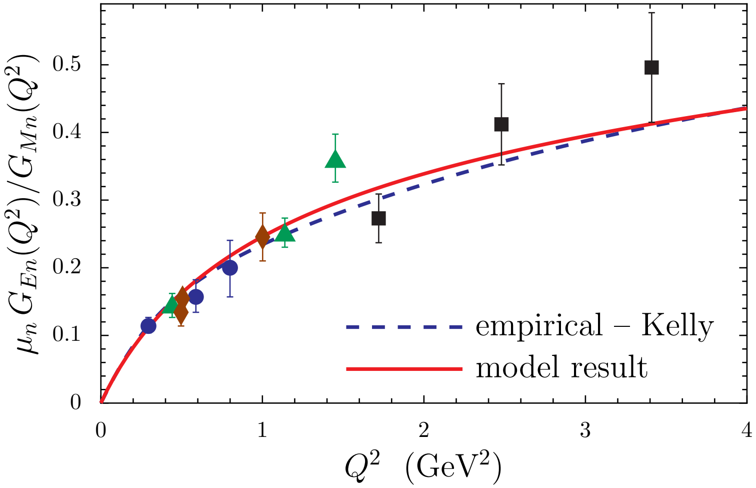


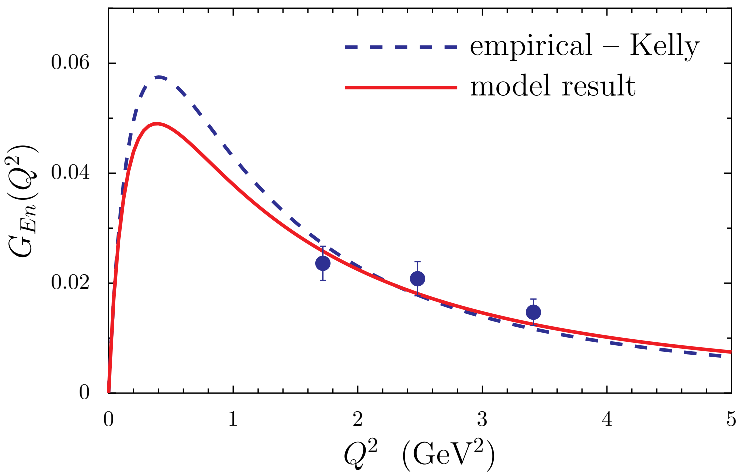
Data Jones, Gayou, Puckett, Perdrisat, Punjabi etc

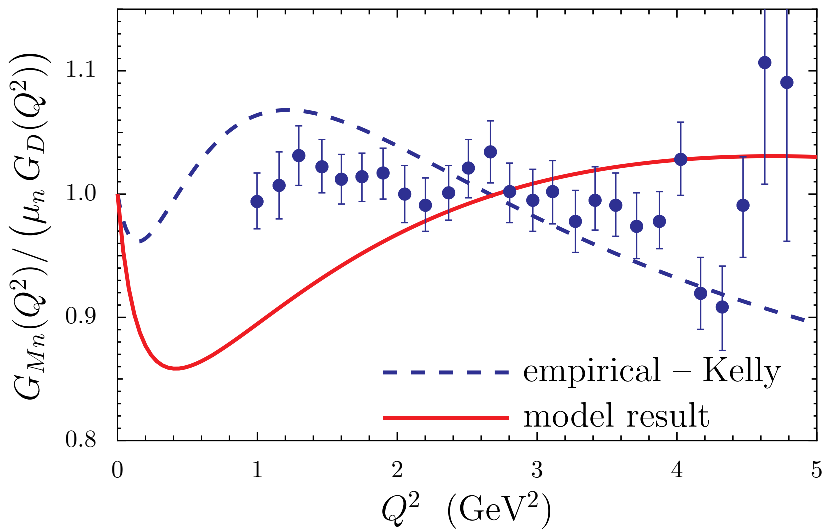


Neutron form factors





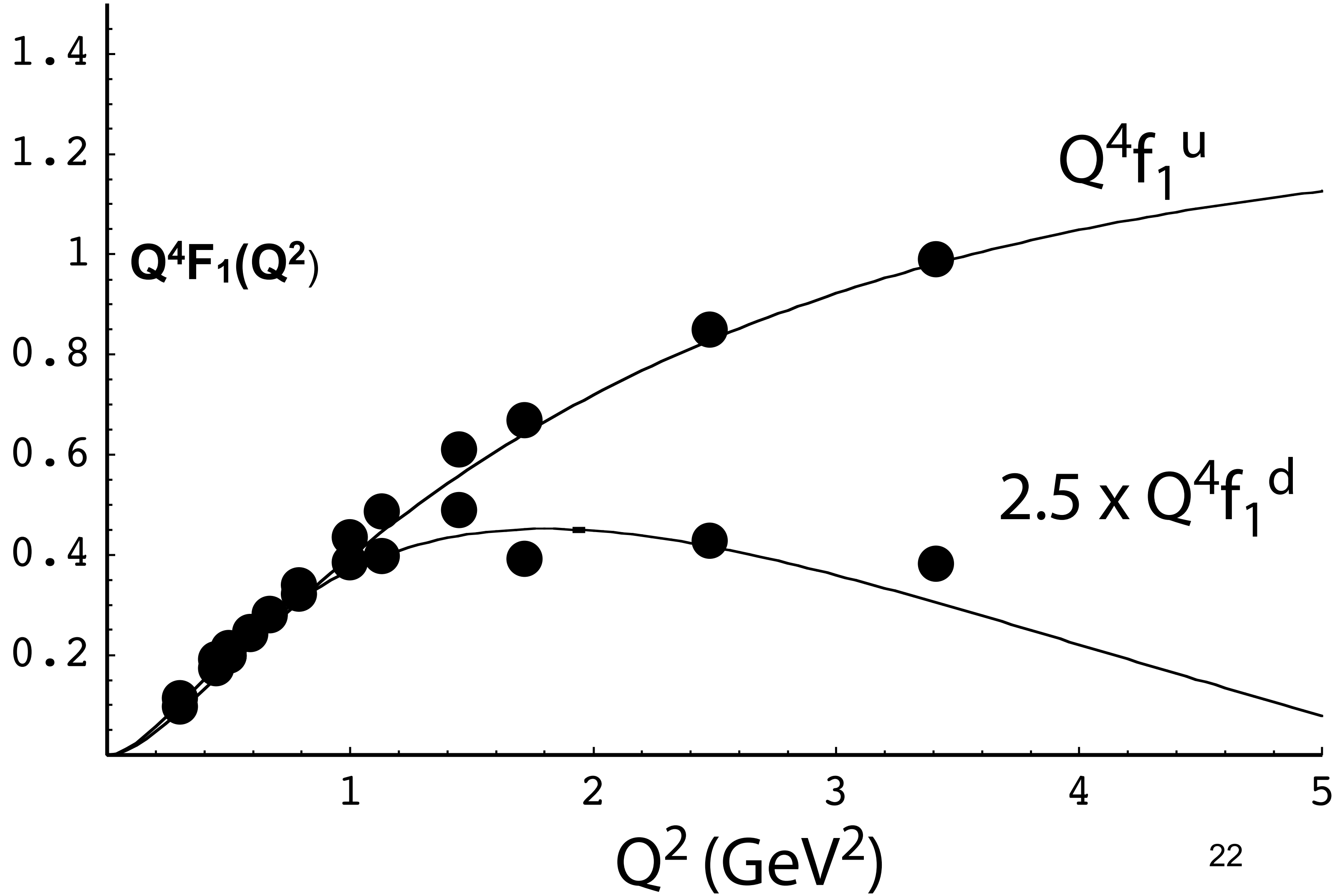




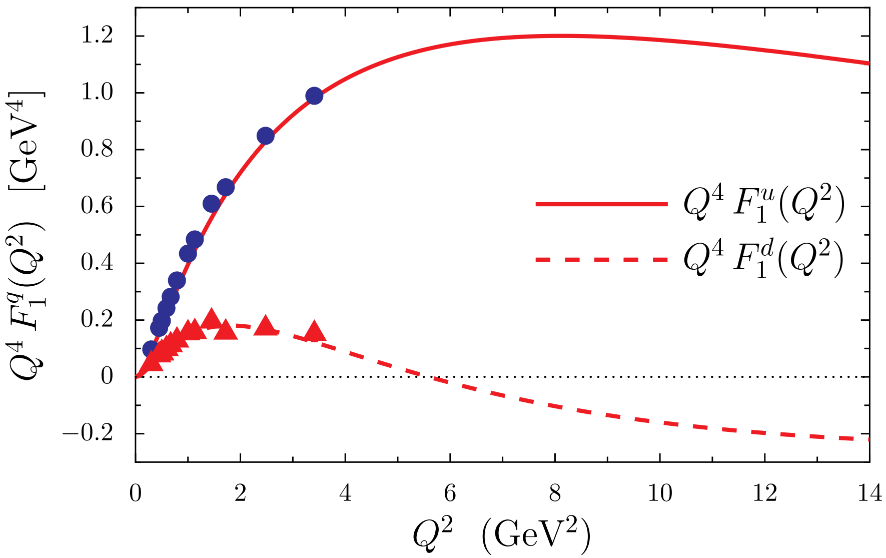
Riordan et al data

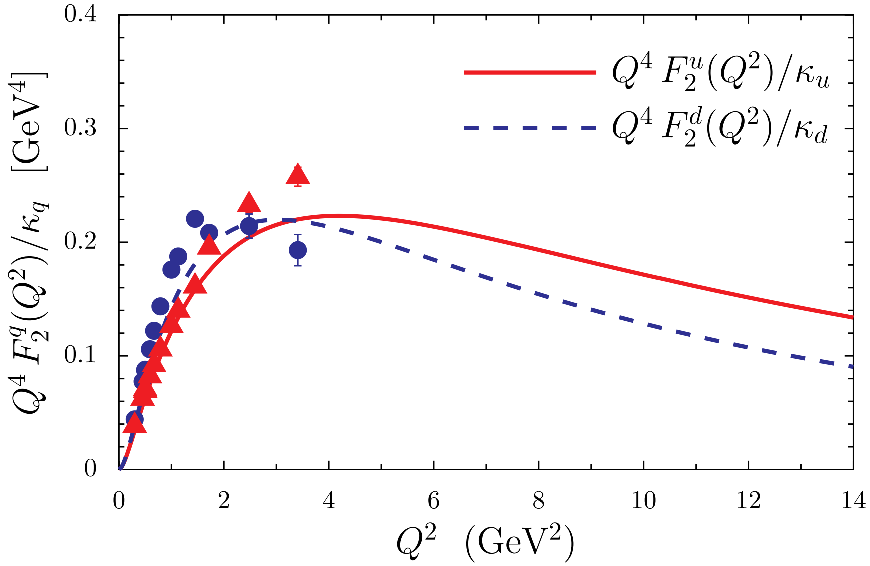
Data Lachniet et al

Flavor separation: Cates, de Jager, Riordan, Wojtsekhowski PRL 106,252003



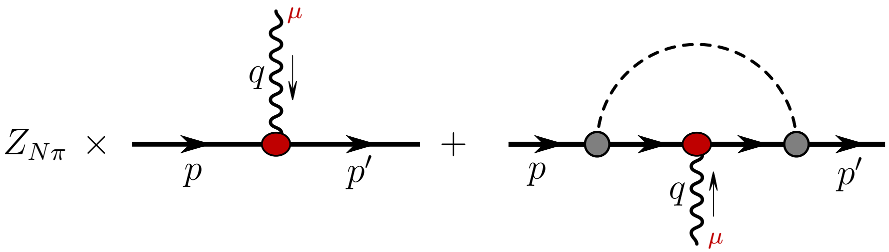
More flavor separation





Data
Cates et al
Jones et al
Gayou et al
Gayou et al
Puckett et al
Riordan et al
Zhu et al
Bermuth et al
Warren et al
Glazier et al
Plaster et al

Quark-Diquark model -spin content



$$\Delta q = q_+(x) - q_-(x), \quad \Delta\Sigma = \Delta u + \Delta d, \ \text{NRQM}\ \Delta u = 4/3, \ \Delta d = -1/3$$

$$\Delta u = \frac{3}{2}\Delta q_s + \frac{1}{2}\Delta q_a, \ \Delta d = \Delta q_a = -0.424$$

$$\Delta q_s = 0.754, \ \Delta u = 0.921, \qquad \Delta\Sigma = 0.497 \text{ no pion cloud}$$

$$\Delta\Sigma_\pi = (Z_{N\pi} + \Delta q_N^\pi)(\Delta u + \Delta d) = (0.706 + \underline{0.281})(0.497) = 0.365$$

10

No gluons, so effects of quark orbital angular momentum

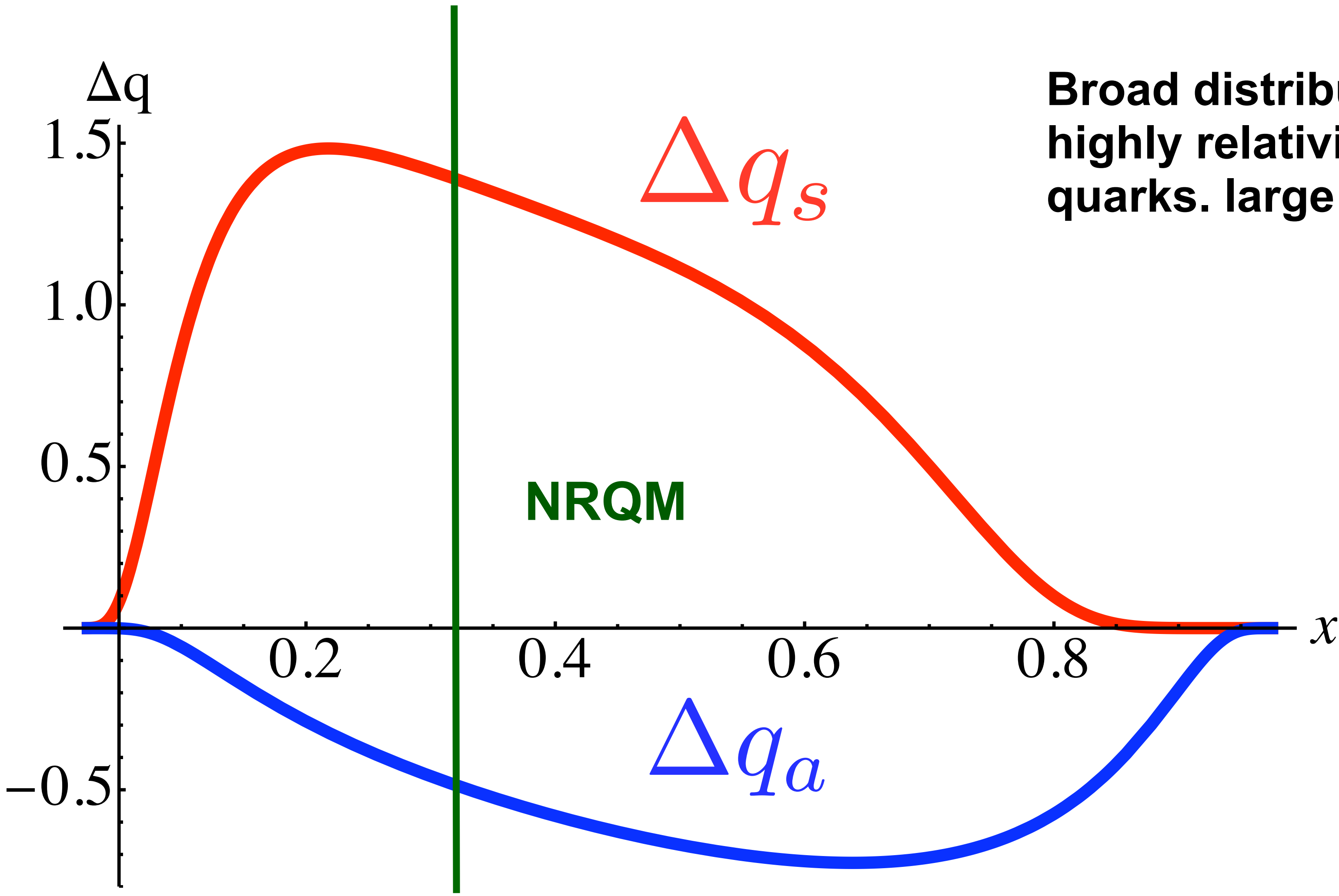
Changes to naive quark model are modest, not revolutionary

Understanding Parameters and spin content

χ^2	m	M_s	M_a	c_s	β_s	γ_s	c_a	β_a	γ_a	Λ	μ_p (μ_N)	μ_n (μ_N)
0.078516	0.191	0.414	0.167	1.509	1.226	5.719	0.008	1.104	8.586	1.035	2.794	-1.849

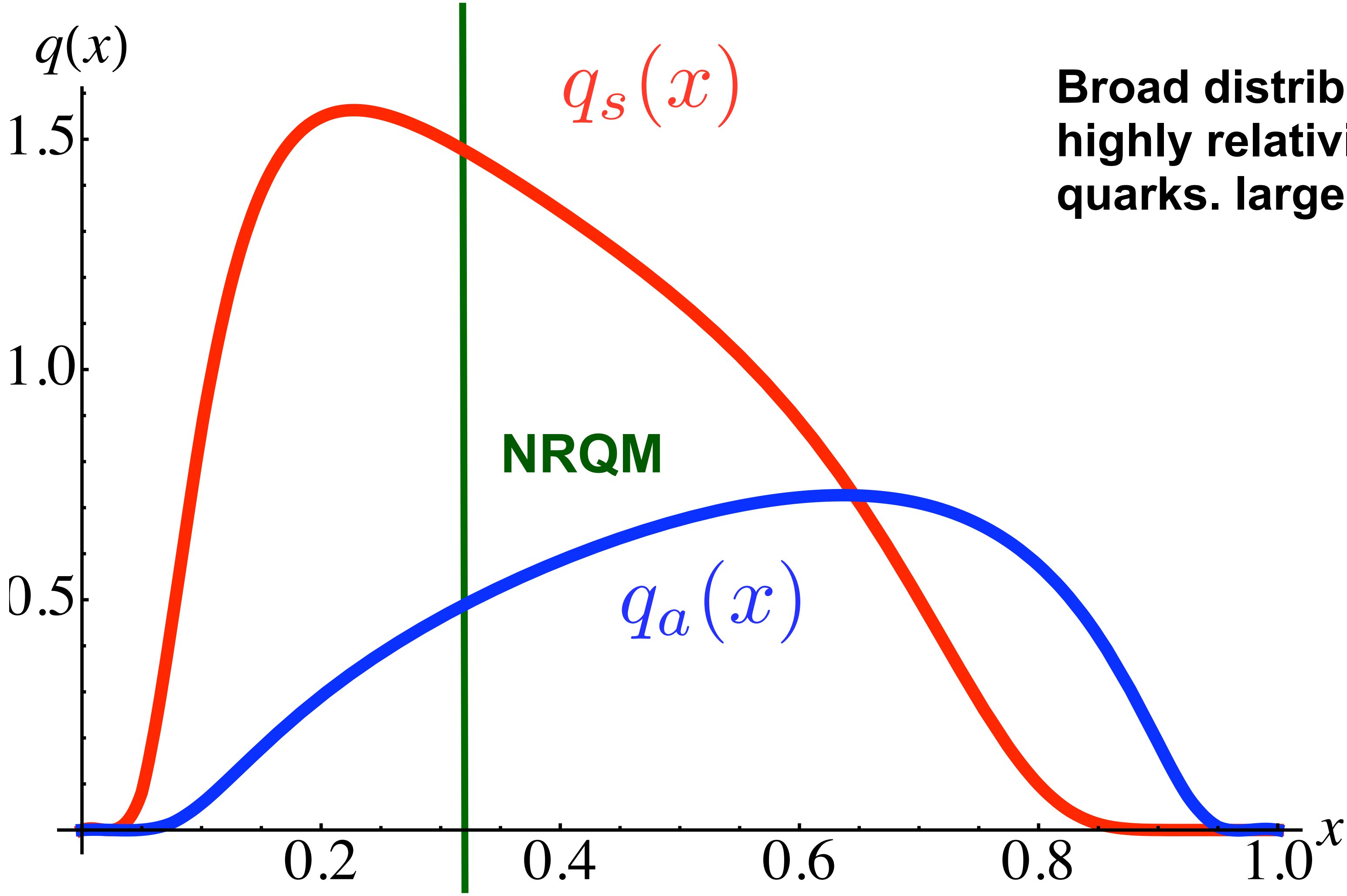
- Lighter quark mass 191 vs 267 MeV
- Relativistic effects are larger than in earlier models, therefore more OAM
- Axial vector di-quark has enhanced components with quark spin opposing proton spin, signature of OAM

Integrands for spin content



Broad distribution in x: highly relativistic quarks. large OAM

Quark distribution q(x)-non evolved



Broad distribution in x: highly relativistic quarks. large OAM

Summary

- Relativistic light front quark model with pion cloud can reproduce nucleon form factors
- Flavor separation works and is testable in the future
- Model quark spin is 36.5 % of total angular momentum, quark OAM is important
- (Relativistic) quark model alive and well, proton is made mainly of three quarks